ANNEX P

Methodology for Estimating Net Changes in Carbon Stocks in Mineral and Organic Soils

This annex presents a discussion of the methodology used to calculate annual carbon flux from mineral and organic soils under agricultural management, based on changes in soil organic carbon storage. The methodology uses a modified version of the IPCC method and a Monte Carlo uncertainty analysis, with the most detailed data available for the United States. As part of this analysis, U.S.-specific reference carbon stocks and management factor values were derived, along with their uncertainty as represented in probability density functions. These were used to estimate soil organic carbon stocks for 1982, 1992, and 1997, which coincide with the years of the *1997 National Resources Inventory* (NRCS 2000). More detailed discussions of selected topics may be found in the references cited in this annex. The details of carbon conversion factors and step-by-step details of calculating net CO_2 flux for mineral and organic soils are given in four steps.

Step 1: Obtain Data on Climate, Soil Types, Land-Use and Land Management Activity Over Time, and Estimate Management Factors Quantifying the Effect of Management Change on Soil Organic Carbon Storage

Step 1a: Climate and Soils

The IPCC inventory methodology for agricultural soils divides climate into eight distinct zones based upon average annual temperature, average annual precipitation, and the length of the dry season (IPCC/UNEP/OECD/IEA 1997) (see Table P-1). Six of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001).

Table P-1: Characteristics of the IPCC Climate Zones that Occur in the United States

Climate Zone	Annual Average Temperature (˚C)	Average Annual Precipitation (mm)	Length of Dry Season (months)
Cold Temperate, Dry	< 10	< Potential Evapotranspiration	NA
Cold Temperate, Moist	< 10	≥ Potential Evapotranspiration	NA
Warm Temperate, Dry	10 – 20	< 600	NA
Warm Temperate, Moist	10 – 20	≥ Potential Evapotranspiration	NA
Sub-Tropical, Dry*	> 20	< 1,000	Usually long
Sub-Tropical, Moist (w/short dry season)*	> 20	1,000 – 2,000	< 5

* The climate characteristics listed in the table for these zones are those that correspond to the tropical dry and tropical moist zones of the IPCC. They have been renamed "sub-tropical" here.

Climate in the United States is monitored through an extensive network of National Weather Service cooperative weather stations. Other national agencies also maintain specific climate databases such as the USDA-NRCS Snotel network and the National Climatic Data Center Global Gridded Upper Air Statistics database. The Parameter-elevation Regressions on Independent Slopes Model has combined the 1961 through 1990 averages from each of these sources with topographic information derived from digital elevation models, generating a grid (4 km x 4 km grid cells) of temperature and precipitation estimates for the United States (Daly et al. 1994, Daly et al. 1998). Average annual precipitation and average annual temperature were derived for the 180 Major Land Resource Areas in the United States from Parameter-elevation Regressions on Independent Slopes Model outputs, and an IPCC climate zone was assigned to each Major Land Resource Area (see Figure P-1). Each Major Land Resource Area represents a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS 1981).

Figure P-1. Major Land Resource Areas by IPCC Climate Zone

Soils were classified into one of seven classes based upon texture, morphology, and ability to store organic matter (IPCC/UNEP/OECD/IEA 1997). Six of the categories are mineral types and one is organic (i.e., histosol). Reference carbon stocks, representing estimates from conventionally managed cropland, were computed for each of the mineral soil types across the various climate zones, based on pedon data from the National Soil Survey Characterization Database (NRCS 1997) (see Table P-2). These stocks are used in conjunction with management factors to compute the modified carbon stocks that result from management and land-use change. Probability density functions, which represent the variability in the stock estimates, were constructed as normal densities based on the mean and variance from the pedon data. Pedon locations were clumped in various parts of the country, which reduces the statistical independence of individual pedon estimates. To account for this lack of independence, samples from each climate by soil zone were tested for spatial autocorrelation using the Moran's I test, and variance terms were inflated by 10 percent for all zones with significant p-values.

Table P-2: U.S. Soil Groupings Based on the IPCC Categories and Dominant Taxonomic Soil, and Reference Carbon Stocks (Metric Tons C/ha)

IPCC Inventory Soil Categories	USDA Taxonomic Soil Orders	Climate Regions					
		Cold Temperate, Dry	Cold Temperate, Moist	Warm Temperate, Dry	Warm Temperate, Moist	Sub-Tropical, Dry	Sub-Tropical, Moist
High Clay Activity Mineral Soils	Vertisols, Mollisols, Inceptisols, Aridisols, and high base status Alfisols	42 (n = 133)	65 (n = 526)	37 (n = 203)	51 (n = 424)	42 (n = 26)	57 (n = 12)
Low Clay Activity Mineral Soils	Ultisols, Oxisols, acidic Alfisols, and many Entisols	45 (n = 37)	52 (n = 113)	25 (n = 86)	40 (n = 300)	39 (n = 13)	47 (n = 7)
Sandy Soils	Any soils with greater than 70 percent sand and less than 8 percent clay (often Entisols)	24 (n = 5)	40 (n = 43)	16 (n = 19)	30 (n = 102)	33 (n = 186)	50 (n = 18)
Volcanic Soils	Andisols	124 (n = 12)	114 (n = 2)	124 (n = 12)	124 (n = 12)	124 (n = 12)	128 (n = 9)
Spodic Soils	Spodosols	86 (n=20)	74 (n = 13)	86 (n=20)	107 (n = 7)	86 (n=20)	86 (n=20)
Aquic Soils	Soils with Aquic suborder	86 (n = 4)	89 (n = 161)	48 (n = 26)	51 (n = 300)	63 (n = 503)	48 (n = 12)
Organic Soils*	Histosols	NA	NA	NA	NA	NA	NA

* Carbon stocks are not needed for organic soils.

Notes: Carbon stocks are for the top 30 cm of the soil profile, and were estimated from pedon data available in the National Soil Survey Characterization database (NRCS 1997); sample size provided in parentheses.

Step1b: Land Use and Management Activity Data

Land use and management data for 1982, 1992, and 1997 were obtained from the *1997 National Resources Inventory* (NRCS 2000). The *1997 National Resources Inventory* is a stratified multi-stage design, where primary sample units are stratified on the basis of county and township boundaries defined by the U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit, typically a 160-acre (64.75 ha) square quarter-section, three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land use information (Nusser and Goebel 1997). An extensive amount of soils, land use, and land management data are collected during each survey, which occurs every five years (Nusser et al. 1998). Primary sources for data include aerial photography and remote sensing materials as well as field visits and county office records.

Land use information in the *1997 National Resources Inventory* was merged into a set of land use and management systems relevant for the soil organic carbon calculations based on the IPCC method (see Table P-3). Each National Resources Inventory point was assigned to a system based upon the land use data collected in 1982, 1992, and 1997 (NRCS 2000). Each National Resources Inventory point contains information on land use from the inventory year as well as three previous years. The four years of land use data were used to assign National Resources Inventory points to an agricultural system. Inventory data for the years 1979 through 1982 were used to define the 1982 land use, 1989 through 1992 for the 1992 land use, and 1994 through 1997 for the 1997 land use. National Resources Inventory points were assigned an IPCC soil type using soil taxonomy and texture information in the soils database that accompanies the *1997 National Resources Inventory* data (NRCS 2000). In addition, points were assigned to an IPCC climate zone based on location within Major Land Resource Areas. More than 400,000 National Resources Inventory points were included in the inventory calculations that had been identified as cropland or grazing land in 1992 or 1997. Each point represents a specific land area based upon the weighted expansion factors.

Table P-3. Land Use and Management Categories

General Land Use		IPCC Category	
Categories	Specific Management Related Sub-Categories	Mineral Soils	Organic Soils
Agricultural (Cropland and Grazing Land)			
	Irrigated Crops	High Input Cultivation	Cultivated Crops
	Continuous Row Crops	Medium Input Cultivation	Cultivated Crops
	Continuous Small Grains	Medium Input Cultivation	Cultivated Crops
	Continuous Row Crops and Small Grains	Medium Input Cultivation	Cultivated Crops
	Row Crops in Rotation with Hay and/or Pasture	High Input Cultivation	Cultivated Crops
	Small Grains in Rotation with Hay and/or Pasture	High Input Cultivation	Cultivated Crops
	Row Crops and Small Grains in Rotation with Hay and/or Pasture	High Input Cultivation	Cultivated Crops
	Vegetable Crops	Low Input Cultivation	Cultivated Crops
	Low Residue Annual Crops (e.g., Tobacco or Cotton)	Low Input Cultivation	Cultivated Crops
	Small Grains with Fallow	Low Input Cultivation	Cultivated Crops
	Row Crops and Small Grains with Fallow	Low Input Cultivation	Cultivated Crops
	Row Crops with Fallow	Low Input Cultivation	Cultivated Crops
	Miscellaneous Crop Rotations	Medium Input Cultivation	Cultivated Crops
	Continuous Rice	Improved Land[1]	Undrained
	Rice in Rotation with other crops	Improved Land[1]	Undrained
	Continuous Perennial or Horticultural Crops	Improved Land[1]	Pasture/Forest
	Continuous Hay	Uncultivated Land (General)	Pasture/Forest
	Continuous Hay with Legumes or Irrigation	Improved Land[1]	Pasture/Forest
	Conservation Reserve Program	Uncultivated Land (Set-aside)	Undrained
	Rangeland	Uncultivated Land (General)	Undrained
	Continuous Pasture	Uncultivated Land (General)	Pasture/Forest
	Continuous Pasture with Legumes or Irrigation	Improved Land[1]	Pasture/Forest
	Aquaculture[2]	Not Estimated	Not Estimated
Non-Agricultural[3]			
	Forest	Uncultivated Land (General)	Pasture/Forest
	Federal	Uncultivated Land (General)	Undrained
	Water[2]	Not Estimated	Not Estimated
	Urban Land[2]	Not Estimated	Not Estimated
	Miscellaneous[2,4]	Not Estimated	Not Estimated

Note: These land use and management categories were derived through analysis of the *1997 National Resources Inventory* data (NRCS 2000).

[1] Improved land increases soil organic carbon storage above the levels found in general land-use changes.

[2] Assume no change in carbon stocks when converting to or from these land uses because of a lack of information about the effect of these practices on soil organic carbon storage.

[3] Some non-agricultural land is included in the inventory because it was an agricultural land use in 1992 or 1997.

[4] Includes a variety of land uses from roads, beaches, and marshes to mining and gravel pits.

Probability density functions for the *1997 National Resources Inventory* land use data were assumed to be multivariate normal, and they were constructed to have a mean vector equal to the vector of total areas in different land use categories for different years of inventory, and to have a covariance matrix equal to the sampling covariance matrix computed from the *1997 National Resources Inventory* data. Through this approach, interdependencies in land use were taken into account resulting from the likelihood that current use is correlated with past use.

Data on tillage practices are not reported in the *1997 National Resources Inventory*, but have been collected by the Conservation Technology Information Center (CTIC 1998). Each year the Conservation Technology Information Center conducts a Crop Residue Management survey to estimate the portion of cropland managed under the various tillage systems. Probability density functions were constructed for the Conservation Technology Information Center data as bivariate normal on a log-ratio scale, to reflect negative dependence among tillage classes and to ensure that simulated tillage percentages were non-negative and summed to 100 percent. Conservation Technology Information Center data do not differentiate between continuous and intermittent use of no-tillage, which is important for estimating soil organic carbon storage. Thus regional-based estimates for continuous no-tillage (defined as 5 or more years of continuous use) were modified based on consultation with

Conservation Technology Information Center experts (downward adjustment of total no-tillage acres reported, Towery 2001).

Wetlands enrolled in the Conservation Reserve Program have been restored in the Northern Prairie Pothole Region through the Partners for Wildlife Program funded by the U.S. Fish and Wildlife Service. The amount of restored wetlands was estimated from contract agreements (Euliss and Gleason 2002). While the contracts provide reasonable estimates of the amount of land restored in the region, they do not provide the information necessary to estimate uncertainty. Consequently, a nominal ±50 percent range was used to construct the probability density functions for the uncertainty analysis.

Probability density functions for manure and sludge application on cropland and grazing land have not been developed because minimal data exist on where and how much manure and sludge has been applied. Consequently, the impact of manure management on soil organic carbon was not part of the base inventory calculation (i.e., uncertainty analysis). Rather, a separate estimation was made for the contribution of manure and sludge management to soil C stocks, and the resulting changes were combined with the uncertainty calculation during post processing.

The amount of manure nitrogen and sewage sludge nitrogen produced each year, including the amount of each that was available for application on agricultural lands, was provided in the Agricultural Soil Management section of the Agriculture chapter of this volume. Manure and sewage sludge nitrogen were assumed to be applied at the assimilative capacity for crops (Kellogg et al. 2000). Assimilative capacity is the amount of nutrients taken up by a crop and removed at harvest, and it may vary from year to year because it is based on specific crop yields during the respective year (Kellogg et al. 2000). Total manure nitrogen and sewage sludge nitrogen available for application was divided by the assimilative capacity to estimate the total land area over which the manure and sewage sludge had been applied. Supplemental data are available regarding the amount of cropland area receiving manure and sewage sludge for major crops in the United States (ERS 2000). The percentage of fields receiving manure and sewage sludge had been estimated between 1990 and 1997 for corn, soybeans, winter wheat, cotton, and potatoes. This information was used in conjunction with the USDA *National Agricultural Statistics Database* (NASS 2002), which provides information on the amount of land planted to each crop, for estimating the cropland area receiving manure and sewage sludge. The remaining area receiving manure and sewage sludge was assumed to occur in grazing lands (calculated as the difference between the total area receiving manure and sewage sludge and the cropland area receiving manure and sewage sludge).

Step 1c: Management Factors Quantifying the Effect of Land Use and Management Change on Soil Organic Carbon Storage

Management factors representative of U.S. conditions were estimated from published studies. The numerical factors quantify the impact on soil organic carbon storage resulting from changing land use and management on soil organic carbon storage, including tillage practices, cropping rotation or intensification, and land conversions between cultivated and native conditions (including set-asides in the Conservation Reserve Program). Studies from the United States and Canada were used in this analysis under the assumption that they would best represent management impacts for this inventory. Also, studies had to report soil organic carbon stocks (or information to compute stocks), depth of sampling, and the number of years since a management change. The data were synthesized in linear mixed-effects models, accounting for both fixed and random effects. Fixed effects included depth, number of years since a management change, and the type of management change (e.g., reduced tillage vs. no-till). For depth increments, the data were not aggregated for the carbon stock measurements; each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) was included as a separate point in the dataset. Similarly, time series data were not aggregated in these datasets. Consequently, random effects were needed to account for the interdependence in times series data and the interdependence among data points representing different depth increments from the same study. Factors were estimated for the effect of management practices at 20 years for the top 30 cm of the soil (see Table P-4). Variance was calculated for each of the U.S. factor values, and used to construct probability density functions with a normal density. In the IPCC method, specific factor values are given for improved pastures and for wetland rice, both of which yield carbon stocks higher than for nominal uncultivated systems. The higher stocks are associated with increased productivity and C inputs (relative to native grasslands) on improved pastures and reduced decomposition due to periodic flooding in rice cultivation. (Improved pastures are identified in the *1997 National Resources Inventory* as pastures that were irrigated or seeded with legumes.). There were insufficient field studies to re-estimate factor values for these systems and thus the IPCC defaults were used, along with a nominal ±50 percent range to construct the probability density function for the uncertainty analysis.

Table P-4. Management Factors for the United States and the IPCC Default Values

	IPCC default	U.S. factor
Land-Use Change		
Cultivated[1]	1	1
General Uncultivated[1,2]	1.4	1.3 (±0.04)
Set-Aside[1]	1.25	1.2 (±0.03)
Improved Pasture Lands[3]	1.1	1.1
Wetland Rice Production[3]	1.1	1.1
Tillage		
Conventional Till	1	1
Reduced Till	1.05	1.02 (±0.03)
No-till	1.1	1.13 (±0.03)
Input		
Low	0.9	0.94 (±0.01)
Medium	1	1
High	1.1	1.074(±0.03)

[1] Factors in the IPCC documentation (IPCC/UNEP/OECD/IEA 1997) were converted to represent changes in soil organic carbon storage from a cultivated condition rather than a native condition.

[2] Default factor was higher for aquic soils at 1.7, but the U.S. analysis showed no significant differences between aquic and non-aquic soils and so a single U.S. factor was estimated for all soil types.

[3] A U.S. specific factor was not estimated for land or management leading to additional carbon storage because of few studies addressing the impact of legume mixtures, irrigation, or manure applications for pasture lands in the United States, or the impact of wetland rice production in the United States.

Wetland restoration management also influences soil organic carbon storage because restoration leads to higher water tables and inundation of the soil for at least part of the year (Olness et al. in press, Euliss et al. in prep). A management factor was estimated assessing the difference in soil organic carbon storage between restored and unrestored wetlands enrolled in the Conservation Reserve Program (Olness et al. in press, Euliss et al. in prep, Euliss and Gleason 2002), which represents an initial increase of carbon in the restored soils over the first 10 years (see Table P-5). A probability density function with a normal density was constructed from these data based on results from a linear regression model. Following the initial increase of carbon, natural erosion and deposition leads to additional accretion of carbon in these wetlands. Mass accumulation rate of organic carbon was estimated using annual sedimentation rates (cm/yr) in combination with percent organic carbon, and soil bulk density (g/cm^3) (Euliss and Gleason 2002). Procedures for calculation of mass accumulation rate are described in Dean and Gorham (1998); the resulting rate and variance were used to construct a probability density function with a normal density (see Table P-5).

Table P-5. Factor Estimate for the Initial Increase in Carbon During the First 10 Years Following Wetland Restoration of Conservation Reserve Program; Mass Accumulation Rate Represents Additional Gains in Carbon After the First 10 Years

Factor (Initial Increase—First 10 Years)	1.22±0.18
Mass Accumulation (After Initial 10 Years)	0.79±0.05 Mg C/ha-yr

Note: Mass accumulation rate from Euliss and Gleason (2002).

In addition, carbon loss rates were estimated for cultivated organic soils based on subsidence studies in the United States and Canada (see Table P-6). Probability density functions were constructed as normal densities based on the mean carbon loss rates and associated variances.

Table P-6: Carbon Loss Rates from Organic Soils Under Agricultural Management in the United States, and the IPCC Default Rates (Metric Ton C/ha-yr)

	Cropland		Pasture / Forest	
Region	IPCC	U.S. Revised	IPCC	U.S. Revised
Cold Temperate, Dry & Cold Temperate, Moist	1	11.2±2.5	0.25	2.8±0.5[1]

Warm Temperate, Dry & Warm Temperate, Moist	10	14.0±2.5	2.5	3.5±0.8[1]
Sub-Tropical, Dry & Sub-Tropical, Moist	20	14.0±3.3	5	3.5±0.8[1]

[1] There were not enough data available to estimate a U.S. value for C losses from managed pastures and forests. Consequently, estimates are 25 percent of the values for cropland, which was an assumption used for the IPCC default organic soil C losses on pasture/forest lands.

Step 2: Estimate Land-Use and Management Activity Trends

Each National Resources Inventory point contains land-use information for the inventory year and the three previous years, which were used to assign each agricultural National Resources Inventory point to a land use/management system (see Table P-3). National Resources Inventory points that were not designated agricultural management in 1992 or 1997 were eliminated from the land base. However, a limited number of points classified as non-agricultural land uses did remain in the analysis. For example, non-agricultural land uses were included if a National Resources Inventory point was cropland or grazing land in 1992 or 1997, but was a non-agricultural land use in 1982. In addition, non-agricultural uses appeared in the land base if a National Resources Inventory point became a non-agricultural use in 1997 after being cropland or grazing land in 1992.

Land areas were summed to evaluate trends in the activity data between 1982 and 1997 for the IPCC land use and management categories (see Table P-7). Between 1997 and 2001, no changes were assumed to have occurred in the relative areas of the agricultural systems with the exception of additional enrollment in the Conservation Reserve Program (discussed later in this document).

Table P-7: Areas for each Land-Use and Management System Used in IPCC Method for all U.S. Land Area Categorized as an Agricultural Use in 1992 or 1997 (Million Hectares)

	Land Areas		
IPCC Land Use/Management Categories	**1982**	**1992**	**1997**
Medium Input Cropping	87.49	77.17	78.27
High Input Cropping[1]	22.21	22.02	21.74
Low Input Cropping[2]	30.96	28.92	25.13
Rice[3]	2.71	2.13	2.22
Uncultivated Land[4]	210.04	207.77	210.26
Improved Land[5]	31.19	33.65	31.43
Conservation Reserve Program[6]	0.00	13.78	13.23
Urban, Water, Miscellaneous Non-Cropland	1.78	0.96	4.11
Totals	**386.39**	**386.39**	**386.39**

Note: Based on analysis of the *1997 National Resources Inventory* data (NRCS 2000).

1 Includes hay or legumes in rotation, winter cover crop, and irrigated cropland.

2 Includes fallow and low residue cropland.

3 The rice areas in this table do not match those in the Rice Cultivation section of the Agriculture chapter because here, rice areas include both fields under continuous rice production and fields under rice in rotation with other crops (e.g., a year of rice followed by a year of wheat production). Therefore, for any particular year, the rice area in this table, representing rice-dominated management systems, is greater than the area under rice production in that year. The rice areas in the Rice Cultivation section of the Agriculture chapter include only areas that are under rice production in each year.

4 Includes hayland, rangeland, pasture, forest, and federal land-use.

5 Includes pasture or hayland with legumes or irrigation and continuous perennial crops.

6 Includes set-aside land.

The trends showed a decline for the area in the high, low, and medium input cropping systems between 1982 and 1997. In addition, the rice-dominated area declined slightly over this time period. A portion of the loss in cultivated cropland was due to setting-aside areas from production in the Conservation Reserve Program, and the remaining decline can be attributed mostly to increases in urban areas, land covered in water (e.g., lakes), and miscellaneous non-cropland (e.g., barren areas and roads). The amount of area in other uncultivated land uses, including pastures and rangelands, remained relatively stable across this time period.

Almost no cropland was managed using no-till in 1982 (see Table P-8). Some land managers, however, had started using reduced tillage systems. For the most part, adoption of reduced tillage and no-till increased steadily in the late 1980s and early 1990s, and leveled off somewhat in the mid- to late- 1990s (CTIC 1998). Because adoption of these conservation tillage techniques has leveled off, adoption was assumed to remain constant between 1997 and 2001 for this analysis. Overall, conventional tillage is the dominant management practice used in U.S. croplands over the inventory period.

Table P-8: Tillage Percentages for each Management Category in the U.S. Climate Zones, with Adjustments for Long-term Adoption of No-till Agriculture (Percent)

System	1982 No Till[1]	1982 Reduced Till[2]	1982 Conventional Till[3]	1992 No Till	1992 Reduced Till	1992 Conventional Till	1997 No Till	1997 Reduced Till	1997 Conventional Till
Sub-Tropical, Dry									
Continuous Cropping Rotations[4]	0	3	97	0	4	96	0	15	85
Rotations with Fallow[5]	0	0	100	0	2	98	0	5	95
Low Residue Agriculture[6]	0	3	97	0	4	96	0	10	90
Sub-Tropical, Moist									
Continuous Cropping Rotations	0	0	100	0	20	80	1	10	89
Rotations with Fallow	0	0	100	0	10	90	1	10	89
Low Residue Agriculture	0	3	97	0	4	96	0	5	95
Warm Temperate, Dry									
Continuous Cropping Rotations	0	0	100	0	10	90	1	15	84
Rotations with Fallow	0	3	97	0	15	85	2	20	78
Low Residue Agriculture	0	3	97	0	1	99	0	0	100
Warm Temperate, Moist									
Continuous Cropping Rotations	0	6	94	10	30	60	12	28	60
Rotations with Fallow	0	6	94	5	30	65	8	27	65
Low Residue Agriculture	0	9	91	1	10	89	2	13	85
Cold Temperate, Dry									
Continuous Cropping Rotations	0	3	97	2	25	73	8	12	80
Rotations with Fallow	0	6	94	4	25	71	12	13	75
Low Residue Agriculture	0	0	100	1	2	97	2	6	92
Cold Temperate, Moist									
Continuous Cropping Rotations	0	11	89	5	30	65	3	17	80
Rotations with Fallow	0	11	89	5	30	65	3	27	70
Low Residue Agriculture	0	0	100	1	2	97	1	7	92

[1] No-till includes CTIC survey data designated as no-tillage.
[2] Reduced-till includes CTIC survey data designated as ridge tillage, mulch tillage, and reduced tillage.
[3] Conventional till includes CTIC survey data designated as intensive tillage and conventional tillage.
[4] Medium and high input rotations (based on the IPCC categories) found in Table P-3. CTIC survey data for corn, soybeans, and sorghum were used in this category.
[5] Rotations with fallow found in Table P-3. CTIC survey data on fallow and small grain cropland were used in this category.
[6] Low input rotations found in Table P-3, with the exception of rotations with fallow. CTIC survey data on cotton were used in this category; tillage rates are assumed to be the same for low residue crops and vegetables in rotation.

Organic soils are categorized into land-use systems based on drainage for purposes of estimating carbon losses (IPCC/UNEP/OECD/IEA 1997). Undrained soils are treated as having no loss of organic C for purposes of the inventory. Drained soils are subdivided into those used for cultivated cropland, which are assumed to have high drainage and greater losses of carbon, and those used for managed pasture or agroforestry, which are assumed to have less drainage and smaller losses of carbon. Overall, organic soils cultivated for cropland production have remained relatively stable since 1982, but the area of organic soils managed as forest or pasture has increased slightly (see Table P-9).

Table P-9: Land Areas for Each Organic Land Use Category (For All U.S. Land Area Categorized as Agricultural in 1992 or 1997) Based on Analysis of *1997 National Resources Inventory* Data. (Million Hectares)

IPCC Land Use Category for Organic Soils[1]	Land Areas 1982	Land Areas 1992	Land Areas 1997
Undrained	0.17	0.19	0.16
Managed Pasture and Forest (Low Drainage)	0.49	0.50	0.52
Cultivated Cropland (High Drainage)	0.63	0.62	0.63
Other Land Uses[2]	0.05	0.02	0.03
Total	**1.34**	**1.34**	**1.34**

[1] Table P-4 provides information how the IPCC land use systems are classified in the land management categories for organic soils.
[2] Urban, water, and miscellaneous non-cropland, are not included in the inventory calculations because they are not agricultural uses and little is known about how they affect soil carbon storage relative to agricultural land management.

The annual areas of mineral soil agricultural lands on which manure and sewage sludge were applied were estimated to range from 23 to 25 million hectares between 1990 and 2001 (see Table P-11 for calculations). Of this total area, manure and sewage sludge applications were estimated to range from 7.5 to 9.5 million hectares of cropland and 14 to 17 million hectares of grazing land.

Step 3: Estimate Soil Carbon Stocks

The IPCC method is a carbon accounting approach that is used to estimate carbon stock changes and CO_2 fluxes between soils and the atmosphere based on land use and management (IPCC/UNEP/OECD/IEA 1997). For mineral soils (i.e., all soil orders from the USDA taxonomic classification except histosols), the IPCC inventory method uses reference carbon values to establish baseline carbon stocks that are modified through agricultural activities as quantified by land-use change, tillage, and input factors. For this inventory, the standard approach was modified to use agricultural soil organic carbon stocks as the reference condition, rather than uncultivated soils under native vegetation. This modification was needed because soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997). Measurements of soils under native vegetation are uncommon in the major agricultural regions of the United States because most of the area has been converted into cropland.

Organic soils used for agricultural production are treated in a separate calculation. These soils are made up of deep (greater than 30 cm) layers of organic material that can decompose at a steady rate over several decades following drainage for cropland production (IPCC/UNEP/OECD/IEA 1997). The IPCC approach uses an emission factor to estimate annual losses of CO_2 from organic soils, rather than a stock change approach.

Mineral and organic soil calculations were made for each climate by soil zone across the United States. Mineral stock values were derived for 1982, 1992, and 1997 based on the land use and management activity data in conjunction with appropriate reference carbon stocks, land-use change, tillage, input and wetland restoration factors. Carbon losses from organic soils were computed based on 1992 and 1997 land use and management in conjunction with the appropriate carbon loss rate.

Each input to the inventory calculations had some level of uncertainty that was quantified in probability density functions, including the land use and management activity data, reference carbon stocks, and management factors. A Monte Carlo Analysis was used to quantify the uncertainty in carbon change for the inventory period based on uncertainty in the inputs. Input values were randomly selected from the probability density functions in an iterative process to estimate soil organic carbon change 50,000 times, and produce a 95 percent confidence interval for soil organic carbon change in agricultural lands.

Step 4: Estimate Average Annual Changes in Soil Carbon Stocks

In accordance with IPCC methodology, annual changes in mineral soil carbon were calculated by subtracting the beginning stock from the ending stock and dividing by 20. For this analysis, the base inventory estimate for 1990 through 1992 is the annual average of 1992 stock minus the 1982 stock. Annual average change between 1993 and 2001 is the difference between the 1997 and 1992 carbon stocks. Using the Monte Carlo Approach, soil organic carbon stock change for mineral soils was estimated 50,000 times between 1982 and 1992, and between 1992 and 1997. From the final distribution of 50,000 values, a 95 percent confidence interval was generated based on the simulated values at the 2.5 and 97.5 percentiles in the distribution. For organic soils, annual losses of CO_2 were estimated for 1992 and 1997 by applying the Monte Carlo approach to 1992 and 1997 land use data and the U.S. carbon loss rates (see Table P-6). The results for 1992 were applied to the years 1990 through 1992, and the results for 1997 were applied to the years 1993 through 2001. On average, mineral soils under agricultural management were sequestering about 35.8 to 35.4 Tg CO_2 Eq. annually and organic soils lost about 34.3 to 34.8 Tg CO_2 Eq. annually (see Table P-10). Overall, U.S. agricultural soils appear to be sequestering from 0.7 to 1.5 Tg CO_2 Eq. annually, although the uncertainties are rather large, ranging from emissions of about 24.2 Tg CO_2 Eq. annually to sequestration of about 19.5 Tg CO_2 Eq. annually.

Table P-10: Annual Change in Soil Organic Carbon for U.S. Agricultural Soils Based Upon the Monte Carlo Uncertainty Analysis with U.S. Factor Values, Reference Carbon Stocks, and Carbon Loss Rates (Tg CO_2 Eq.)

	1990-1992	1993-2001
Mineral Soils	(35.8)*	(35.4)*

	(13.9 to 58.7)	(20.9 to 50.3)
Organic Soils	34.3	34.8
	23.1 to 48.4	23.5 to 49.1
Total	**(1.5)**	**(0.7)**
	24.2 to (27.2)	**19.5 to (19.5)**

*Does not include the change in storage resulting from the annual application of manure or the additional Conservation Reserve Program enrollment after 1997.

Note: The ranges are a 95 percent confidence interval from 50,000 simulations (Ogle et al. in review).

There are two additional land use and management activities in U.S. agriculture lands that were not accounted for in the base inventory (i.e., uncertainty analysis). The first activity involved the application of manure and sewage sludge to agricultural lands. Minimal data exist on where and how much manure and sewage sludge is applied to U.S. agricultural soils, but national estimates of mineral soil land area receiving manure and sewage sludge are available by combining information from the USDA *National Agricultural Statistics Database* (NASS 2002), manure and sewage sludge nitrogen applications (from the Agricultural Soil Management Section of the Agriculture chapter of this Inventory), and USDA Economic Research Service reports on percentage of fields receiving manure for major crops in the United States (ERS 2000). The impact of manure and sewage sludge additions on soil organic carbon was calculated as 0.1 metric ton C/ha-yr for croplands, and 0.33 metric ton C/ha-yr for grazing lands. These rates are based on IPCC calculations that represent the effect of converting medium input cropping systems to high input systems and on converting nominal pastures to improved lands, respectively (assuming a reference carbon stock of 50 metric ton C/ha-yr, which represents a mid-range value for the dominant agricultural soils in the United States). From 1990 through 2001, manure and sewage sludge applications in agricultural lands increased soil organic carbon storage in mineral soils by about 5.79 to 6.26 Tg C annually (21.3 to 23.0 Tg CO_2 Eq.) (see Table P-11).

Table P-11: Assumptions and Calculations to Estimate the Contribution to Agricultural Soil Organic Carbon from Application of Animal Manure and Sewage Sludge to Mineral Soils

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Total N (Tg)[1]	**2.76**	**2.84**	**2.83**	**2.90**	**2.92**	**2.90**	**2.94**	**3.00**	**3.04**	**3.04**	**3.09**	**3.11**
Manure N[1]	2.71	2.78	2.77	2.83	2.85	2.82	2.85	2.91	2.95	2.94	3.00	3.01
Sewage Sludge N[1]	0.05	0.06	0.06	0.07	0.08	0.09	0.09	0.09	0.09	0.09	0.10	0.10
Assimilative Capacity (metric ton / ha)[2]	**0.120**	**0.120**	**0.120**	**0.122**	**0.122**	**0.122**	**0.122**	**0.122**	**0.122**	**0.122**	**0.122**	**0.122**
Area covered by Available N (ha x 10^6)[3,4]	**22.98**	**23.64**	**23.61**	**23.75**	**23.97**	**23.78**	**24.08**	**24.59**	**24.89**	**24.90**	**25.36**	**25.47**
Cropland Receiving Manure	7.78	8.58	8.04	8.42	8.51	6.69	8.66	9.27	9.30	9.17	9.34	9.34
Grazing Land Receiving Manure	15.20	15.06	15.57	15.32	15.46	17.09	15.42	15.32	15.59	15.73	16.02	16.13
Contribution to Agricultural Land Soil C (Tg C)[5]	**5.79**	**5.83**	**5.94**	**5.90**	**5.95**	**6.31**	**5.95**	**5.98**	**6.07**	**6.11**	**6.22**	**6.26**
Contribution to Cropland Soil C	0.78	0.86	0.80	0.84	0.85	0.67	0.87	0.93	0.93	0.92	0.93	0.93
Contribution to Grazing Land Soil C[5]	5.01	4.97	5.14	5.06	5.10	5.64	5.09	5.06	5.14	5.19	5.29	5.32

[1] Total N available to be applied to soils (this volume).

[2] Assimilative Capacity is the national average amount of sewage sludge and manure-derived N that can be applied on cropland without buildup of nutrients in the soil (Kellogg et al. 2000).

[3] Area which received manure or sewage sludge amendments was calculated based on the available N for application divided by the assimilative capacity. The 1992 assimilative capacity rate was applied to 1990 - 1992 and the 1997 rate was applied to 1993-2000.

[4] Some small, undetermined fraction of this applied N is probably not applied to agricultural soils, but instead is applied to forests, home gardens, and other lands

[5] Soil C stock is calculated as the area covered by available N multiplied by a national average annual rate of soil C change per ha (0.1 metric ton/ha-yr for croplands and 0.33 metric ton/ha-yr for grazing lands).

The second activity, which is not included as part of the baseline inventory, is the change in enrollment for the Conservation Reserve Program after 1997. Relative to the enrollment in 1997, the total area in the Conservation Reserve Program declined in 1998 through 2000, and then increased in 2001, leading to an additional enrollment of 362,377 ha over the four year period (Barbarika 2002). An average annual change in soil organic carbon of 0.5 metric ton C/ha-yr was used to estimate the effect of the enrollment changes. This estimate was based on an IPCC calculation for how much soil organic carbon increases by setting aside a medium input cropping system in the Conservation Reserve Program (assuming a reference carbon stock of 50 metric ton C/yr, which represents a mid-range value for the dominant agricultural soils in the United States). The change in enrollment generated emissions in 1998 through 2000, but with increased enrollment by 2001, agricultural lands sequestered an additional 0.7 Tg CO_2 Eq. in 2001 relative to the baseline inventory (see Table P-12).

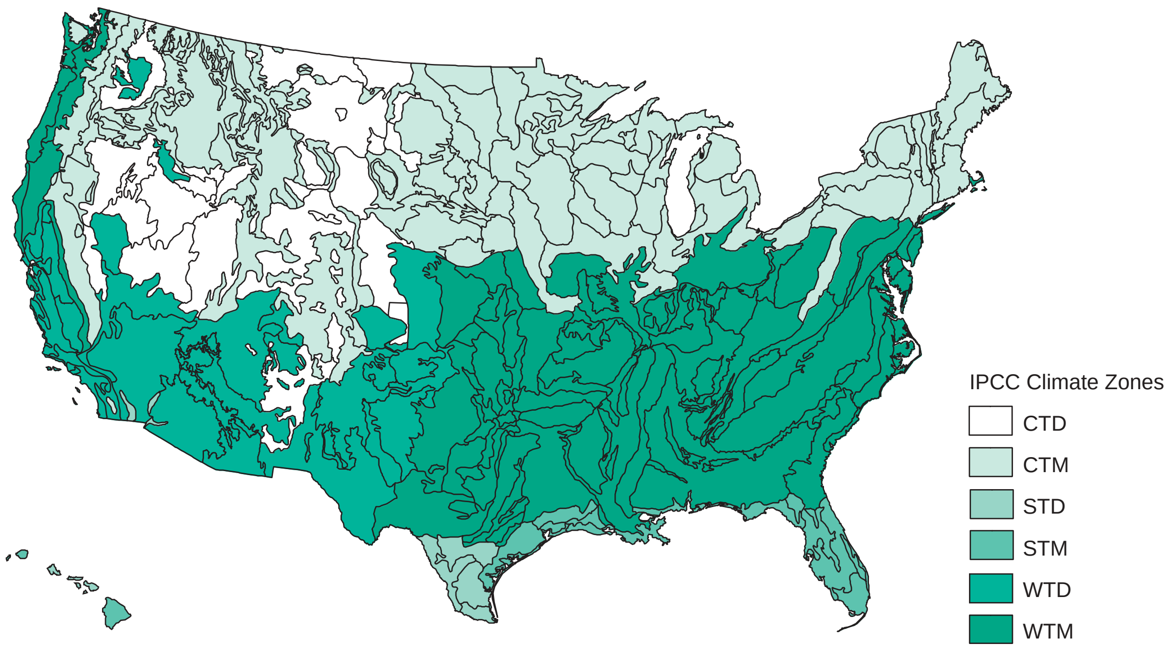
The sum total of the base inventory and the additional land use and management considerations (i.e., manure and sewage sludge additions, and Conservation Reserve Program enrollment in 1998 through 2001) are presented in Table P-12. Agricultural soils were estimated to sequester from 21.0 to 24.3 Tg CO_2 Eq. annually between 1990 and 2001, based on the change in soil organic carbon storage.

Table P-12: Annual Net Flux of CO_2 from U.S. Agricultural Soils for the Baseline Inventory (Uncertainty Analysis) Plus the Additional Land Use/Management Considerations (Tg)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Net emissions based on uncertainty analysis	**(1.5)**	**(1.5)**	**(1.5)**	**(0.7)**	**(0.7)**	**(0.7)**	**(0.7)**	**(0.7)**	**(0.7)**	**(0.7)**	**(0.7)**	**(0.7)**
Mineral Soils	(35.8)	(35.8)	(35.8)	(35.4)	(35.4)	(35.4)	(35.4)	(35.4)	(35.4)	(35.4)	(35.4)	(35.4)
Organic Soils	34.3	34.3	34.3	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8
Additional changes in net emissions from mineral soils	**(21.3)**	**(21.4)**	**(21.8)**	**(21.7)**	**(21.9)**	**(23.2)**	**(21.9)**	**(22.0)**	**(20.4)**	**(20.3)**	**(21.9)**	**(23.6)**
Application of manure and sewage sludge N to crop and grazing lands	(21.3)	(21.4)	(21.8)	(21.7)	(21.9)	(23.2)	(21.9)	(22.0)	(22.3)	(22.4)	(22.8)	(23.0)
Changes in Conservation Reserve Program enrollment relative to 1997	NA	NA	NA	NA	NA	NA	NA	NA	1.9	2.1	0.9	(0.7)
Total net emissions	**(22.8)**	**(22.9)**	**(23.3)**	**(22.3)**	**(22.5)**	**(23.8)**	**(22.5)**	**(22.6)**	**(21.1)**	**(21.0)**	**(22.6)**	**(24.3)**

Figure P-1

Major Land Resource Areas by IPCC Climate Zone



This figure shows the IPCC climate zone assigned to each of the 180 Major Land Resource Areas (MLRAs) in the United States, based on PRISM climate data averaged for each MRLA.